Optical Communications Technologies for High Data Volume Returns from Deep Space

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Abstract— NASA communications roadmaps look to space based optical communications to fulfill future high data rate link requirements with minimal spacecraft burden and freedom from current RF spectrum restrictions. Efficient optical links for data rates from 10's to over 1000 megabits per second require complementary and synchronized development of numerous subsystem technologies. We report recent developments and performance of Serial Concatenated Pulse Position Modulation coding, high data rate pulse position optical modulators, high power laser amplifier, efficient photon counting detector, and high background (daytime) photon counting receiver technologies for the photon starved channel

I. Introduction

EFFICIENT free space optical communications links can fulfill future NASA communication requirements at multi-hundreds of megabits per second data rates, including projected gigabit per second returns from deep space projected for 2020 and beyond [1,2]. However, the required link subsystems technologies, including transmitter, receiver, coding, and channel technologies, are entirely different than existing RF technologies. Some technologies, such as precision pointing, optical antenna development, and forward error correction coding, are essentially data rate independent. Others, such as laser modulation, optical detector, and receiver/decoder electronics, have implementations that are very data rate dependent. In order to be accepted operationally, the optical link must be able to provide substantially higher data rates and data return volumes than an equivalent mass and power RF system, and at a lower cost per bit. Some recent advances in data rate dependent technologies are reported herein.

II. Data Rate Technologies

A. Modulation and Coding

High capacity can be achieved by combining photon counting detection with signal encoding on a high peak-to-average power laser transmitter and pulse position modulation [3,4]. The efficient Serial Concatenated Pulse Position Modulation (SCPPM) code [5] can be applied to achieve a less than one dB gap to capacity. In 2005, a real-time 6 megabits per second SCPPM decoder was demonstrated in an emulated Mars link [6]. That real-time rate has now been extended on the same hardware to 60 megabits per second through firmware optimization, and a new custom board design with optical fiber interconnects for a distributed decoder array has now been completed that is linearly scalable to SCPPM data rates over 1000 megabits per second (Fig. 1).

B. High Rate Pulse Position Modulaton

Efficient PPM communications beyond 100 require sub-nanosecond slot widths. To meet this need, JPL has developed a series of Field Programmable Gate Array (FPGA) encoders and modulators that operate a slot rates down to 100 picoseconds with real time data inputs to 1.2 gigabits per second (Fig. 2). The FPGA based encoder also performs real-time SCPPM encoding, which is considerably less resource intensive than SCPPM decoding. Slot widths down to 25 picoseconds are achieved by multiplexing multiple PPM encoders through commercial fiber-optic multiplexers. The resulting electrical signals are then used to modulate a continuous wave seed laser using commercial 10 and 40 GHz fiber optic components (Fig. 3), followed by high power laser amplification.

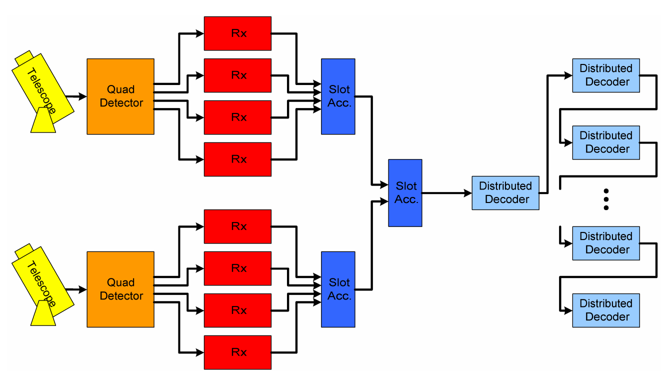

Fig. 1. Scalable optical receiver architecture with distributed decoder.

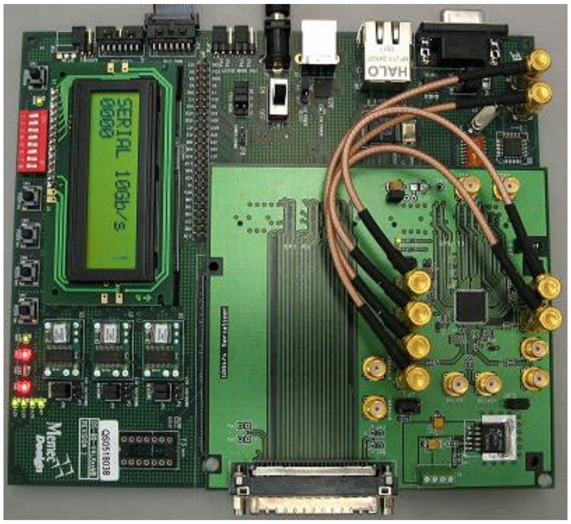

Fig. 2. JPL 100 picosecond slot width PPM serializer mounted onto prototype 1.2 gigabit per second SCPPM encoder board.

C. *High Power Laser Amplifier*

High order PPM requires an efficient laser amplifier with a high peak to average power ratio. This requirement can be met with Yb fiber lasers operating near 1060 nm [7] or Er/Yb fiber lasers operating near 1550 nm, with the highest DC to optical efficiencies presently achievable at the shorter wavelength. Recently we have begun testing fiber amplifiers with average powers in the 1 to 10 Watt range and peak powers in the 100's of Watt range originally designed for nanosecond PPM slot widths for their amplification behavior on sub-nanosecond pulses with widths as narrow as 5 picoseconds. Across this pulse width range, Stimulated Brillouin Scattering (SBS) is not limiting, but Self Phase Modulation (SPM) becomes the dominant nonlinear effect limiting laser performance at pulse widths less than 100 picoseconds with the existing fiber amplifier designs (for example, Fig. 5).

D. *Photon Counting Detector*

Efficient detectors reduce spacecraft burden by reducing the amount of transmit laser power required. High single photon detection efficiency (SPDE) and low output pulse jitter are required for reception of PPM signals at high data rates. Dark count rate requirements are less stringent than other photon counting applications due to the high background fluxes encountered during daytime link operations, and detector count rate limitations (linearity) can be mitigated through the use of array architectures.

The detectors of choice for the cancelled Mars Laser Communications Demonstration were the InGaAsP intensified photodiode (IPD) [8], and arrays of Geiger Mode InGaAsP/InP avalanche photodiodes (GM-APD) [9]. Both devices photon count in the near-infrared with high efficiency (> 40% SPDE) and operate with minimal cooling (250K). However, the IPD is a vacuum tube device that suffers from photocathode degradation with lifetime, and the GM-APD requires complicated reset and readout circuitry for high duty cycle.

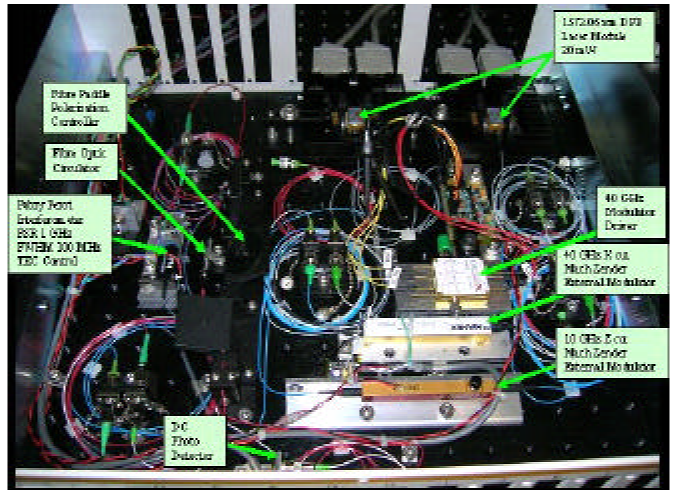

Fig. 3. 40 GHz optical PPM modulator test bed

Recently, the superconducting niobium nitride (NbN) detector [10] has been investigated extensively, despite it's requirement for cooling to liquid helium temperatures, due to its potential for near 100% detection efficiency and demonstrated single photon pulse jitter on the order of 20 picoseconds. The Microdevices Laboratory at JPL is presently the sole U.S. grower of thin (4 to 6 nanometers) NbN films and has fabricated eight element arrays (Fig. 6) and single pixels with up to 40% detection efficiency [11] and 22 picoseconds jitter for a 5 micron square device.

We are also progressing in demonstrating Negative Avalanche Feedback (NAF) avalanche photodiodes with InGaAs absorbers for non-Geiger mode photon counting in the near infrared. This technology has been previously demonstrated in silicon for visible wavelengths [12]. The NAF operational mode eliminates the requirement for the reset circuitry and read-out electronics of the GM-APD. We have now validated high gains (greater than 10^5) with excess noise factors near 1.0 in an InGaAs/InP material system and confirmed single photon response in non-Geiger mode operation (Fig. 7).

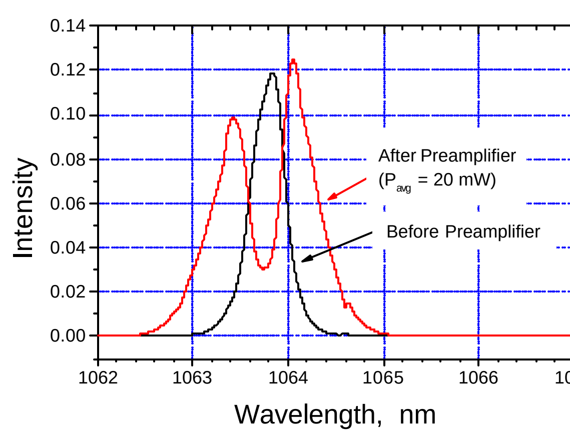

Fig. 5. 500 mW, 1064 nm fiber amplifier output spectrum from 80 MHz, 5 ps input pulse width stream.

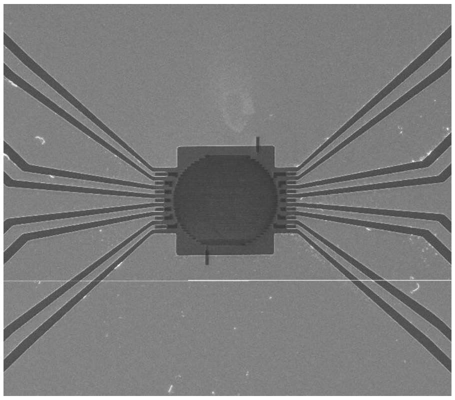

Fig. 6. SEM image of a 14 micron diameter 8 element, 100 nm line width, NbN detector array to match a focused optical spot.

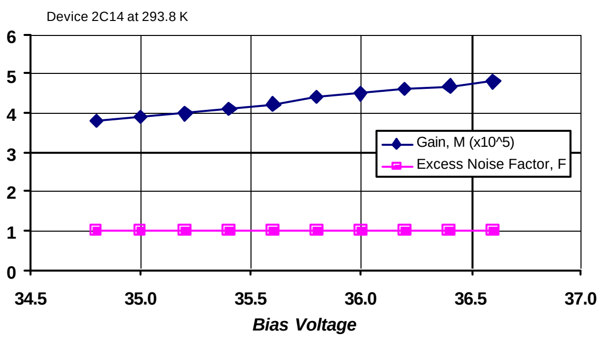

Fig. 7. Gain and excess noise factor for prototype InGaAs NAF detector

E. *Photon Counting Receiver*

To process the photon counting detector output signal, JPL has developed a custom high rate Photon Discriminating Deserializing Interface (PDDI) with subsequent FPGA based digital signal processing to perform the functions of timing synchronization and SCPPM decoding. In 2006 we completed an implementation of the PDDI that operates at an input sample rate of 16 GHz with a 16 to 1 deserialization. In 2007 this interface was integrated with a FPGA based receiver operating with PPM-16 + 1 guard time slot for synchronization, and signal acquisition and tracking has been validated using an InGaAsP IPD photon counting detector on pseudo-random data streams at over 150 megabits per second. The use of the inter-symbol guard time allows a simpler receiver architecture for high data rates [13], versus injecting a periodic laser pulse (pilot tone) to achieve timing acquisition and synchronization under photon starved link scenarios.

III. Emulated Link Performance

The above high rate optical communications technologies have been integrated into an end-to-end test bed and validated in an emulated Mars free space optical communications link at data rates over 50 megabits per second. The data stream

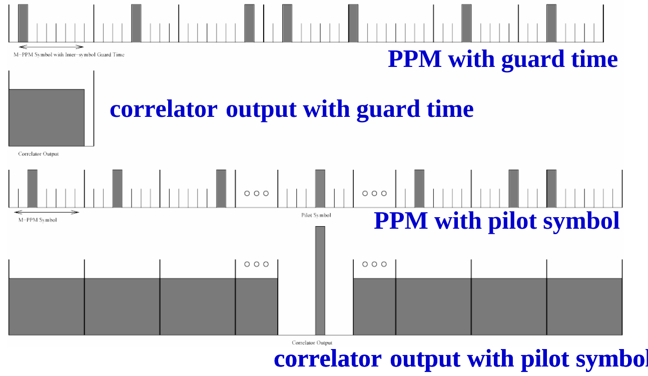

Fig. 8. Inter-symbol guard time versus pilot tone receiver timing synchronization

includes a real-time MPEG-4 encoded High Definition Television (HDTV) channel. We have found that it is necessary to include real data across an emulated link, as with only pseudo-random data problems with acquisition and synchronization may be missed. The emulated link includes real-time SCPPM data encoding and laser modulation, signal attenuation and background light addition to emulate a photon starved deep space link, free space transmission of approximately 6 meters across a lab, signal reception and detection by a photon counting detector (IPD or NAF), and digital receiver timing synchronization followed by SCPPM decoding and MPEG decoding and display of the received HDTV data stream. SCPPM hardware decoder performance has been validated to 1 dB of capacity (Fig. 9) Link statistics are acquired on a pseudo-noise sub-channel, and acquisition, tracking, and decoding have been validated using unsynchronized transmit and receive clocks.

IV. Conclusions and Future Work

Space based optical communications has been demonstrated to date in near-Earth scenarios. Present technology is sufficient to demonstrate efficient communications at Mars distances and data rates of tens of megabits per second [14].

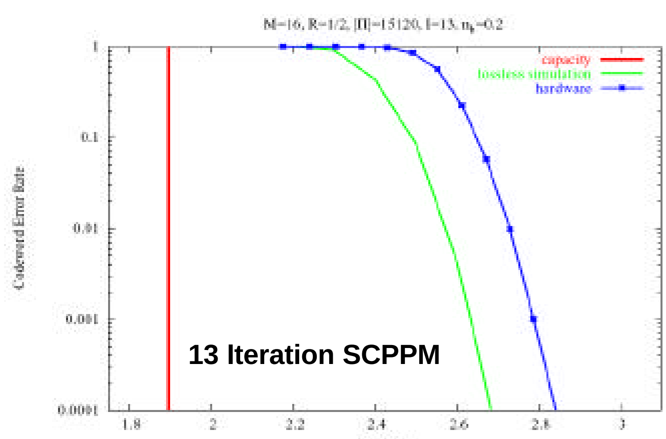

Fig. 9. SCPPM decoder performance for 50 megabit per second emulated Mars link

Further technology development is required, however, to reduce system mass, power, and complexity, to make optical communications systems more palatable for flight operations.

We are presently implementing further custom optical transmitter and receiver electronics to extend our real-time 50 megabit per second end-to-end emulator to demonstrate a real-time capability of over 1000 megabits per second on a photon starved channel. Also, the end-to-end test bed is being migrated to outdoor environments to validate emulated deep space links in the presence of actual day and night sky background, including near sun-pointing operation to within 3 degrees of the sun.

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